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**LOW-COST UNMANNED AIR VEHICLE (UAV)
FOR OCEANOGRAPHIC RESEARCH
Phase I Final Report**

J. J. Kollé

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INTRODUCTION

In this Phase I program conducted for the Office of Naval Research (ONR), we have evaluated the feasibility of deploying a generic unmanned air vehicle (UAV) instrument platform to meet the needs of a wide range of oceanographic research programs. Our objective is to identify or develop a complete UAV system, including ground station, launch and recovery system, and autonomous flight capability, capable of carrying a variety of imaging and measurement instruments at a cost to investigators of under \$50k.

This project was initiated because of a need for a system capable of synoptic aerial photogrammetry of sea ice at a cost less than that of daily helicopter support. A wide variety of existing UAV systems were evaluated for this mission, including radio-controlled (RC) model aircraft, UAVs developed for military reconnaissance, and high-altitude aerosondes recently developed for atmospheric research. It was found that RC model aircraft lack the capabilities for photogrammetry, while existing military and scientific UAVs are expensive to buy and operate. It is also clear that existing UAV systems require significant piloting skills. We therefore initiated the development of a UAV designed specifically for aerial photogrammetry. A survey of oceanographers was conducted in the course of this project to solicit input on other oceanographic research missions for UAVs. This information was used to generate performance specifications for a UAV that would meet the needs of a variety of research programs, including photogrammetry, high-resolution video recording, and radiometry. The feasibility of such a system was demonstrated in this project by obtaining a low-cost military UAV trainer, modifying it to enhance lift and low-speed performance, and carrying out flight tests with a dummy instrument payload.

Piloting an RC aircraft requires skills comparable to or greater than those required to fly an aircraft. This greatly limits the number of researchers capable of using a conventional UAV. We have therefore evaluated options for automated launch, flight control, and recovery of the UAV. A parachute recovery system is proposed for UAV recovery. It has been shown that a 286-PC-based autopilot with simple rate and altitude sensors can provide control signals at a rate sufficient to allow automated launch and flight control of a UAV. An autopilot and parachute recovery system limit the pilot workload to flight planning and extend the availability of the UAV capability to the average researcher. Flight planning and execution can also be carried out by computer, which would allow fully autonomous flight. The development of reliable launch, autopilot, and parachute recovery systems requires a substantial effort, which will comprise the second phase of this project.

This report begins with a presentation of information obtained from oceanographers in a survey conducted through the OMNET computer network. The next section discusses oceanographic research applications that could take advantage of UAV capabilities. Design specifications for an oceanographic research UAV are presented next, including autopilot, navigation, and communication requirements. Existing scientific and military UAV capabilities are then reviewed to show that none of the existing systems is suited to the oceanographic research mission. A design for a UAV capable of meeting the required specifications is presented next. A low-cost UAV was obtained with an airframe of sufficient range, payload capacity, and flight ceiling to carry a Global Positioning System (GPS) navigation system, duplex serial communications, computer autopilot, and instrumentation. The initial performance of this vehicle was inadequate, so the aircraft was modified until the flight performance specifications were met. Design, modifications, and flight test results for this UAV are presented. Conclusions of this Phase I study are given in the final section.

OMNET SURVEY

In order to evaluate interest in low-cost UAVs for oceanographic research, a preliminary description of a UAV was circulated on the OMNET computer network. OMNET is widely used by oceanographers, particularly those involved in field work. A number of replies expressing interest in a low-cost UAV were received and are provided below.

1. Ray Hosker, Director, NOAA Atmospheric Turbulence & Diffusion Division, (615) 576-1248

Some researchers at NOAA are using light aircraft to measure fluxes of certain things (heat, water vapor, CO₂, etc.) and are debating the use of UAVs.

2. Robert Bernstein, SeaSpace Corporation, (619) 578-4010

SeaSpace Corporation is heavily involved with satellite remote sensing. We have installed dozens of small receiving and processing systems around the world to permit people to work with the 1-km resolution imagery from the various weather and environmental satellites. Some of these systems are installed aboard research and other types of vessels. The UAV as you described it would nicely complement some of these systems, particularly the shipboard units. As a particularly apt example, two of these shipboard units are going aboard U.S. Coast Guard icebreakers, another is aboard a German icebreaker. These vessels currently use helicopters for certain types of ice reconnaissance, but I could see the UAV as a valuable alternative. I will be participating in an ONR cruise to the Chukchi Sea this August aboard one of these Coast Guard icebreakers, which should give me some added insight into how/whether the UAV concept would pan out. Our imaging software is quite sophisticated, and we might be interested in participating in the area of incorporating data from one or more UAV imaging sensors into our imaging system, with accurate earth location, for merging/registering the UAV image data with satellite imagery data. Lots of possible paths, which I would imagine the Navy, Coast Guard, and others might take a real interest in!

3. Miles McPhee, McPhee Research, (519) 658-2575

I read with interest your message about the UAV. We are planning a Weddell Sea winter project in Jul-Sep 94 from the new icebreaker, NB Palmer. Originally, there were going to be helos from which aerial photography/photogrammetry would be done for characterizing open water, grey ice, etc., but it appears that budget limitations will axe the helos. Is there any chance of using your UAV? We're late in the proposal process: drop dead for OPP proposals is 1 Jun; however, if there is another way of getting the instrument on the ship, it would be fun to try out, and perhaps very useful for the project as a whole.

4. Reinert Korsnes, Norwegian Polar Institute

Interested in quantitative image analysis of sea ice remote sensing imagery. Have long been looking for such a low-cost UAV possibly connected to field work at Svalbard [where we now have a permanent office (in Longyear-byen)]. I am very interested in using such an instrument connected to monitoring of ice production at some locations of Svalbard. In my paper, Korsnes, R.: "Quantitative analysis of sea ice remote sensing imagery," *International Journal of Remote Sensing*, 1993, 14(2):295-311, I demonstrate some basic (automatic) analyses of video images of sea ice. I introduce some "intelligent control" of such a UAV based on automatic/quantitative image analysis in order to produce good/relevant maps of the ice field. In January-February-March 1994, the ERS1 second ice phase will take place. In connection to process studies in the ice field I would like to have such a UAV available.

5. Jim Yoder, Graduate School of Oceanography, University of Rhode Island

Your UAV sounds interesting. Please keep me informed.

6. Jim Churnside, (303) 497-6744.

I am planning a field experiment for sometime in 1994 to demonstrate fisheries applications of airborne remote sensors. This experiment would take place off the coast of Southern California. This would be a great opportunity to demonstrate UAV video for fish spotting. Most fish spotting is currently done by expert observers in small aircraft, either shore-based fixed-wing or ship-based helicopters. A UAV with enhanced video could potentially replace either of these with a better system at a lower cost and without the risk currently associated with spotting fish. At \$20k, there may be a substantial commercial market for this device.

7. Wendell S. Brown, Director, Ocean Process Analysis Laboratory, University of New Hampshire, (603) 862-3505

Planning a 1994 and 1995 study of physical and biological oceanography of coastal western Gulf of Maine freshwater, along-coast flows. These warm water flows are related to red tides. Interested in radiometric mapping, color visual imaging, and electrical conductivity to map and monitor these flows.

8. Bruce Keafer, Don Anderson, Wayne Rockwell-Geyer, Woods Hole Oceanographic Institute, (508) 457-2000 (x2509)

Carrying out a coastal zone field program to monitor red tides associated with warm freshwater coastal flows from the Kennebec and Merrimac Rivers. These flows are 5-50 km wide along the coast. They are also interested in applying a UAV with a radiometer to monitor a sewer outfall 35 km offshore of Boston.

9. Anthony Michaels, Anthony Knap, Robbie Smith, Melodie Hammer, Bermuda Biological Station for Research, Inc., (809) 297-1880

Interested in remote sensing of ocean color as part of the U.S. JGOFS Bermuda Atlantic Time-series Study (BATS). Would like to fly a still camera, video camera, digital camera, or spectrometer to 3-km altitude. Interested in working 80 to 150 km offshore, i.e., 100 kph with a duration of 3-4 hrs. Also interested in ship launch/recovery to extend range.

10. John. L. Largier, Center for Coastal Studies, Scripps Institute of Oceanography, (619) 534-4333

Interested in near coastal research related to the exchange of water between estuaries and the ocean. This exchange is dominated by tidal processes, rip currents, and small-scale upwelling. Would like to make ocean surface temperature maps, observe the wind fields and the atmospheric boundary layer thickness. Wants to repeat flights at 60-90 minute spacing to monitor temporal evolution of sea surface temperature and other processes and would like to collaborate on a field trial in late 1993 or early 1994.

11. David Jones, Autometrics Inc., (703) 658-4400

Interested in a UAV to fly a multispectral scanner.

12. Raymond Smith, Computer Systems Laboratory, Center for Environmental Optics, University of California, Santa Barbara, (805) 893-4709

Has a long-term NSF-funded program to monitor ecology in Antarctica. Wants to count penguins with a film camera and fly a BSI multispectral sensor that simulates the latest SEAWIFFS imager to look at ocean surface color. They have a small monitoring area (10×20 km) around Palmer Station and a large area (200×1000 km) to monitor. Helicopters are not available because of cost in this area, and they presently use a Zodiac but this is limited to fair weather. He would like to participate in a Phase II demonstration.

13. Andy Jessup, Norbert Untersteiner Applied Physics Laboratory, University of Washington, (206) 685-2609

Have demonstrated infrared scanning and imaging of the sea surface including radiometry of the Arctic ice cover using the Heinmann KT-19 radiometer, mounted on a Twin Otter Aircraft door.

14. Paul Holland, SWL Inc., (805) 964-7724

Have developed a micro gas chromatograph weighing less than 4 kg that could be flown on a UAV for air sampling. Interested in price and delivery to incorporate into a proposal.

15. Dave Karl, Oceanography Department, University of Hawaii, (808) 956-8964

Interested in application of a UAV for the Hawaiian Ocean Time Series Program. They have 5 years of NSF support to map the variability of the upper ocean, and are interested in extending the work to aerosol sampling in the atmosphere. Interested in ocean color measurements to monitor plankton. They would also like to be able to monitor a mooring 100 km off the coast of Oahu. They have NSF funding for ship time on the Moana Wave (a UNOLS ship) to test new techniques and would be willing to provide ship time for sea trials of the UAV.

OCEANOGRAPHIC RESEARCH APPLICATIONS FOR A LOW-COST UAV

Mission profiles and instrumentation for a range of oceanographic research missions for a low-cost UAV are discussed below.

Photogrammetry

The original mission envisioned for the UAV was time-lapse photogrammetry of sea ice deformation. This would involve photographing an area of 1 km² at resolutions sufficient to reveal inelastic deformations of as little as 1 m. Periodic imagery would be combined to define the history of sea ice deformation over periods of weeks or months at a relatively low cost. A 45×60 mm metric camera (e.g., Pentax 645, Table 1) can resolve to less than 1 m over this field of view. This resolution is also compatible with the image processing capabilities of digitizers, PCs, and workstations. Low-distortion photography over a 1-km field of view can be carried out with a 150-mm lens at an altitude of 2200 m (7100 ft). Sequential photogrammetry of sea ice requires that the camera return to the same position relative to a fixed reference point. Returning to the exact three-dimensional position will not be possible, so it will be necessary to correct for image distortions by observing position and attitude. Relative position to within 1 m can be obtained using differential GPS with a fixed ground station and an airborne receiver. This capability will be useful in flying the UAV and will be necessary for all of the applications discussed here.

Aerial photogrammetry is also useful in mapping time-variable coastal features such as sandbars, reefs, and coastlines, for drifter studies and for determining accurate relative positions of instruments on the sea surface.

Table 1. Example Scientific Payloads

Payload	Dimensions, mm	Power, W	Weight, kg
Aerosonde		0	0.25
Sekai 470 line Color CCD Camera	35×25×155	4	0.5
"L" Band Video Transmitter, 2W, 10-km range	110×60×30	15	0.2
2 hours of NiCad battery	---	20	1.5
TOTAL Payload			2.2
Cannon Hi8 Videocamera, 400 lines w/optical image stabilizer, 120 minutes of Hi8 videotape	200×175×60	included	1.2
Sekai 470 line Color CCD Camera	35×25×155	4	0.5
Toshiba V-80AB-F, Hi8 Videotape Recorder, 120 minutes of Hi8 videotape	148×120×161	15	3.0
2 hours of NiCad battery	---	20	1.5
TOTAL Payload			5.0
Heinman KT-19; infrared radiometer, RS232	197V×66×140	3.6	1.5
2 hours of NiCad battery	---	3.6	0.3
TOTAL Payload			1.8
Pentax 645; metric camera with motor drive and 150 mm lens	189V×109×147	included	1.8
Camera Alive DC-1; high-resolution (1242×1152, 8-bit) video imaging system, RS422, 2 Mbytes RAM/image	305V×100×100	24	2.5
Eply integrating radiometer	---	---	3.5
FLIR Systems Infrared Camera (3-5 μ m, 244×320, 10-bit), NTSC Video	235×150×127	25	3.6
Cincinnati Electronics IR Camera IRC-160 (3-5 μ m, 160×120, 12-bit), NTSC Video	368×120×133	25	4.1
BSI Spectral Radiance Sensor	300×75 dia	included	4.5
Linhof Metrika 91×112 mm metric camera, 150-mm lens	250V×240×240	included	8.0
VTT Multispectral Imager (450-900 nm), NTSC Video	332×230×190	15	12.0

Scouting

The shipborne scouting mission is potentially the largest commercial market for a low-cost UAV. An onboard GPS and simplified flight controls would allow scientists and navigators to scout for leads in the vicinity of icebreakers, meteorological fronts, other ships, instruments in the water, animals, men overboard, schools of fish, oil slicks, or whatever; every captain will want one. A short-range (10 km) scout could transmit live video back to the ship for real-time observation. A longer-range system would fly autonomously using a programmed flight path and store the data on an 8-mm tape recorder for analysis onboard the ship.

The scouting mission requires the development of shipborne launch and recovery systems and provisions for a wet landing. A low-cost, waterproof, short-range UAV with only a video camera and transmitter could be developed specifically for this mission.

Time-Averaged Video

Time-averaged video of the breaking wave field on a beach has been used by Rob Holman of Oregon State University to locate subsurface features (sandbars and profile changes) that cause waves of various amplitudes to break. This requires positioning of a video camera in a fixed location for 10 minutes while recording the image. Since coastal winds tend to be reasonably constant, we could essentially fly the camera to the appropriate altitude and hold position by flying into the wind. The data would be transmitted to a recorder on the ground, and we could use the same software to map the location of breaking waves. This would best be done in conjunction with a synoptic research program, but we could certainly demonstrate the procedure on a local beach.

Scanning Radiometry

A number of investigators have expressed an interest in monitoring coastal currents arising from river discharge. These currents are associated with red tides and pollutant transport. The currents can be monitored by profiling sea surface temperature transverse to the coast using a radiometer. Coastal currents may extend out to 100 km from shore, and a UAV-based system would require a range of twice this distance. This mission will require development of a capability for autonomous flight at fixed altitude and course, turning, and homing back to the recovery site.

A variety of lightweight radiometers that could be used for this work are available. For example, the Heinman KT-19 radiometer (Table 1) can record temperature differentials as small as 0.1°C. A typical flight plan would involve a traverse over a feature of interest with data taken at 1 Hz and data storage using solid-state memory or an 8-mm tape, depending on the resolution required.

Integrating Radiometry

Studies of the ocean radiation budget use airborne upward- and downward-looking, integrating radiometers to obtain a measure of radiant heat flux into the ocean. Eply radiometers (Table 1) use a spherical lens to integrate infrared radiation. These instruments are fairly heavy, because they are designed for stability on the ground. They are also sensitive to vertical orientation and may require gimbaling or gyroscopic stabilization.

Ocean Color

Imaging or scanning the ocean color is an important component of oceanographic research involving plankton production and the behavior of fronts. At the simplest level, the ocean color could be obtained by flying over with a high-resolution color video camera and recording the data on tape. More sophisticated approaches involve multispectral imaging scanners, which allow quantitative observation of the ocean color spectral content. Examples of instrumentation include the VTT and BSI multispectral scanners listed in Table 1. The BSI scanner is designed to sample the same spectral bands as the SEAWIFS satellite and is therefore ideally suited to ground truth. The VTT scanner is designed as a highly flexible multispectral airborne imaging system that can be configured for compatibility with the SEAWIFS spectral bands or for other missions.

Atmospheric Sounding

The instrumentation required for measuring temperature, relative humidity, and barometric pressure has been miniaturized for use in dropwindsondes (Table 1). These expendable instruments are designed to be dropped from aircraft, to collect data in free fall, and to transmit the data using an RF transmitter. An aerosonde is essentially the same instrumentation incorporated in an unmanned aircraft. A long-range (20,000 km), high-altitude (20,000 m) aerosonde is currently under development by Aurora Flight Sciences; this system is designed to carry out atmospheric profiling missions over long distances. There is also a need for finer-scale profiling of the atmospheric boundary layer to altitudes of 3 km in support of studies of the flux of momentum, heat, water vapor, and CO₂.

Atmospheric sounding of winds aloft can be carried out by incorporating wind speed and compass heading sensors in the UAV (also required for navigation and flight planning). This application may require a differential GPS capability to obtain an accurate aircraft velocity vector. It should also be possible to observe atmospheric turbulence using accelerometers. The data can be combined with dynamic measurements of temperature and vapor concentration to obtain local flux measurements.

The aerosonde capability is lightweight and should be compatible with sampling missions. This capability would be useful for studies of pollution plumes, oilfield and forest fire smoke, atmospheric releases of nuclear materials, and the ash in volcanic eruptions. Sampling typically requires that a volume of air be drawn through a filter. Lightweight vacuum systems are available and could be integrated into a sampling package for this mission; alternatively, the engine intake vacuum could be utilized.

UAV SPECIFICATIONS FOR OCEANOGRAPHIC RESEARCH

The review given above of instrumentation payloads and mission profiles suggests that a UAV capable of carrying a 4-kg useful payload with a range of 300 km and altitude ceiling of 3 km will be capable of meeting most needs for an oceanographic research platform. We prefer an aircraft with a stall speed of 50 kph or less. This will allow hovering in a breeze for time-lapse photography or for video monitoring of real-time processes. A low stall speed provides greater overall aircraft stability, particularly during launch (when airspeed is low). This stability increases the time available for an autopilot to respond to problems, provides faster recovery from stalls, and also provides more time to navigate accurately. The aircraft should have an endurance of several hours and be capable of speeds of 100 kph or more.

We have required that the UAV provide PC-compatible data acquisition and serial data transmission capability. This provides a standard interface and an open system architecture that is familiar to most of the oceanographic research community and allows for simple integration with a variety of instruments. We will also require GPS navigation and a serial data communications rate sufficient to allow differential GPS positioning.

A central issue for the acceptance of UAVs is reliability. The most unreliable element in UAV operations is a human pilot. UAVs are much more difficult to control than piloted aircraft; the pilot may become confused about aircraft attitude during maneuvers or lose sight of the aircraft altogether. These considerations imply that the UAV must be capable of automated takeoff, flight control, and recovery. Most oceanographic research is carried out at sea and under less than ideal weather conditions. We require that the UAV be weatherproof and compatible with water landings for offshore recovery. The system should also be capable of operations in polar and tropical regions.

Finally, a commercially viable UAV system must be compatible with typical oceanographic research funding levels and logistical support. Discussions with investigators suggest that a system cost of under \$50k would be compatible with the research programs discussed above, provided the UAV has a useful lifetime of several years. These programs typically involve a single investigator with a graduate student or technician for assistance, so we require a system that can be set up and operated by two people. The type of program for which a UAV should be cost-effective is typically located in a remote area, so the system must be compact and easy to transport either in a utility vehicle, such as a pickup truck, or for air freight delivery using a helicopter or small fixed-wing aircraft.

EXISTING UAV SYSTEMS

Scientific UAVs

At the low-cost extreme, researchers have used RC model aircraft to carry instruments. For example, Hess and Aubrey (1985) describe the use of a hobby aircraft (2.4 m Telemaster) to carry a 35-mm camera for drifter and dye current studies in a tidal inlet. Hill (1993) has used a UAV equipped with electrostatic sensors to observe the orientation of the electrical field in the vicinity of thunderstorms.

QUEST has recently pursued the development of an onboard computer capability for an RC model aircraft. The computer would provide autopilot capability and PC-compatible data acquisition and transmission via a duplex RF modem. This internally funded work demonstrated computer control of the aircraft and transmission and display of flight data on a portable PC computer. A parachute recovery system was also demonstrated for this aircraft. The aircraft is limited to one kilogram or less of useful payload, but the control and data transmission scheme are extremely low in cost (<\$1k) and could be adapted to a larger aircraft.

The Perseus-B UAV (Langford and Emanuel, 1993) was developed for the deployment of dropsondes from high altitudes for atmospheric studies. Aurora Flight Sciences, which developed the Perseus, has also investigated the potential for an autonomous aerosonde designed to profile the atmosphere from sea level to 20 km. This system has generated concerns for air traffic safety and requires miniaturization of atmospheric profiling instruments.

The Condor system developed by Boeing is capable of transoceanic flights at high altitudes carrying a large scientific payload. The procurement and operational costs for this aircraft are extremely high, and its future is uncertain.

The basic capabilities and costs of the above-mentioned scientific UAVs are listed in Table 2.

Table 2. UAVs Used for Science

UAV	Cost, 1000\$	Payload, kg	Altitude, km	Range, km
RC Model	1	5	1	1
Perseus	1500	170	20	1000
Condor	50,000	500?	20	20,000

UAV Joint Project Office

The U.S. Congress has directed the Department of Defense (DoD) to consolidate the management of non-lethal UAV programs; this has resulted in the formation of the UAV Joint Program Office (UAV JPO). This office prepares an annual master plan outlining progress in the development and procurement of UAV systems for DoD ("Department of Defense Unmanned Aerial Vehicles (UAV) Master Plan," March 31, 1993, Unmanned Air Vehicles Joint Project Office, Washington D.C.). The UAV JPO has an interest in promoting civil and commercial applications of UAVs in order to achieve cost savings, foster technological innovation, and ensure the growth of a strong U.S. capability for producing UAVs.

We have contacted the UAV JPO to obtain the latest information on UAV technology developed by DoD. A summary of military UAV systems is provided in Table 3.

Military UAVs

Of the UAVs listed in Table 3, the Firebee and Pioneer UAVs have seen the greatest service. The Firebee was used in Vietnam for long-range reconnaissance, including photography and infrared imagery. These systems were configured for autonomous flight, allowing long-range reconnaissance. The Pioneer UAV has gained recognition because of its effectiveness during Desert Storm, where it provided real-time target acquisition and battle damage assessment in day and night operations. The Hunter, Skyeeye, and TRA Model 410 are developmental systems designed to replace the Pioneer. All of these systems use a twin-boom, pusher prop airframe configuration similar to the Pioneer. The range of these systems is limited by the range of the video and control signal transmitters. The relatively high costs are related to the costs of secure radio transmission on the battlefield and sophisticated sensor systems.

A number of UAVs are also under development by foreign countries. Most notable of these is the Ranger UAV, which is being marketed for civilian applications by Oerlikon-Contraves in Switzerland. Typical costs for a short-range (150-km radio link) military UAV is in excess of \$1M. Two of the vehicles listed (Cypher and Eagle Eye) have vertical takeoff and landing (VTOL) capability; both are developmental systems. While a VTOL capability appears to be useful for shipboard launch and recovery, these systems tend to be much more complex than a fixed-wing UAV, and costs are expected to be very high. Reliable landings by VTOL UAVs on the cluttered, moving deck of a ship at sea have not been demonstrated.

Table 3. UAVs Developed with DoD Sponsorship

Manufacturer	Type	Payload, kg	Range, km	Endurance, hr	Cost ¹ , \$	Status
Teledyne Ryan Aeronautical (TRA)	Firebee 147NA, 147SC	--- ²	1000	---	---	Vietnam Era
	Tactical Endurance 410	45	---	24	---	Development
	BQM 145-A High Spced	ATAR	650	2 @ 650 kph	---	Prototype
AAI Corporation and IAI	Pioneer	50 - 100	150	8 - 12	1-3M	Production
TRW and IAI	Hunter	45 - 135	150	8 - 12	1-3M	Development
BAI Aerosystems Inc.	Exdrone	22	60	2.5 @ 130 kph	25k	Production
	Maxdrone	45	60	2.5 @ 250 kph	40k	Production
Aerovironment	Pointer Electric	1	30	2 @ 30 kph	12.5k	Production
Naval Research Laboratory	LAURA / FLYRT Low-Speed Electronic Warfare Decoy	---	---	1 - 20 @ 33 kph	---	Development
Sikorsky	Cypher VTOL	22	30	3	---	Prototype
Bell Helicopter Textron	Eagle Eye VTOL	---	---	---	---	Development

¹Cost - per aircraft, ground costs are typically 2 to 3 times single aircraft cost.

²Do not presently have data.

VTOL - Vertical takeoff and landing.

IAI - Israel Aircraft Industries.

IAT - International Aerospace Technologies.

FLYRT - Flying Radar Target.

Cost - per aircraft; ground station costs are typically 2 to 3 times single aircraft cost.

ATAR - Advanced Target Acquisition and Recognition system developed by Martin Marietta.

Several low-cost systems (<\$50k) have also been developed under DoD sponsorship. The Naval Research Laboratory has been developing a flying radar target (FLYRT) designed to fly at ship speeds (30 kph). This work has included the testing and development of low-Reynolds-number airfoils. (One of these airfoils was chosen to enhance the lift of the QUEST UAV as described below.) The Pointer UAV is a very low cost battlefield reconnaissance system. It is hand launched and uses an electric motor to provide a quiet, short-range video reconnaissance capability; however, its payload and range are small.

The Exdrone (BQM-147a) and Maxdrone systems were designed as expendable UAVs for battlefield support of ground troops. Of all of the systems examined, the Exdrone comes closest in cost and capability to the requirements for an oceanographic research UAV; its capabilities are discussed in detail below.

Exdrone (BQM-147a)

The Exdrone is in production as an expendable very short-range reconnaissance UAV. It has a maximum instrumentation payload capacity of 11 kg and should fly well with a 5-kg payload. Cruise speed is around 150 kph (80 kts), and the range is over 300 km.

The Exdrone has a relatively high takeoff speed (45 kts) and requires a conventional runway for a rolling takeoff. The relatively high takeoff speed places great demands on pilot skills. An 8-m (26-ft) long trailer-mounted launch has been developed to allow launches from other sites. A skilled pilot is still required to transition from launch mode to a steady climb rate and cruise speed. Once this transition has been completed, the onboard autopilot can take over almost all the pilot workload.

The Exdrone 32-bit autopilot with GPS navigation is capable of directing the aircraft to three way points. The "L" band radio has a line of site range of up to 45 km, and a ground station is available to display aircraft position and some flight data. This radio is capable of transmitting all flight control parameters as well as a video signal. The radio is full duplex and can receive control signals to fly the aircraft, alter the flight program, deploy a parachute, or activate an onboard instrument. BAI offers a stabilized video camera option for reconnaissance, and this is the typical flight configuration for the military version.

A parafoil option is available to recover the aircraft. The descent is nearly vertical at a speed of 6 m/s, allowing recovery in a limited open area.

The UAV JPO has coordinated the procurement of 100 Exdrone vehicles from BAI Aerosystems of Easton, Maryland, for use by the Marine Corps and the Army. Testing of these vehicles has been successful, with units logging over 100 flights and 200 flight hours. Exdrone systems are available at the following costs:

Exdrone aircraft	\$12,500
Flight accessories	\$1,000
RC transmitter	\$1,000
32 bit autopilot w/GPS	\$6,500
"L" band transceiver	\$9,000
Parafoil recovery system	\$2,500
Ground station transceiver, power supply & display	\$25,000
Pneumatic launcher	\$10,000
TOTAL	\$69,500

Of all the existing UAV systems considered, the Exdrone came closest to meeting our requirements. However, the speed of this aircraft is relatively high, which causes a number of concerns, in particular:

- The initial flight stability is low, which makes automated control difficult.
- The high cruise speed makes it more difficult to attain a fixed GPS way point.
- Low-speed hover in a breeze for fixed observations is not possible.

In addition, the Exdrone costs are higher than our target, the system is not compatible with water landings, and the autopilot capabilities are limited to only three way points. Finally, the Exdrone has a conventional, engine-forward configuration that could also interfere with the installation of forward-looking instrumentation.

PROPOSED DESIGN

None of the existing UAV systems are compatible with the oceanographic research missions discussed above. We therefore proceeded in this project to demonstrate the feasibility of a purpose-built oceanographic UAV system. Our objective was an aircraft cost of less than \$10,000. In the following subsections, we describe options considered for autopilot and navigation systems and communications data links, and we demonstrate that systems meeting the mission requirements are available in off-the-shelf, standardized configurations at low cost. We also describe the procurement of a low-cost airframe that was modified and flight tested (see next section for results of testing) to demonstrate the payload, speed, and endurance capabilities required. We also demonstrated inner-loop control of the aircraft with a low-cost analog autopilot.

Autopilot and Navigation

A typical aircraft autopilot incorporates two levels of control. There is an inner-loop autopilot that maintains the instantaneous stability of the aircraft for a fixed flight regime, and an outer-loop autopilot that compares the aircraft position with preset way points and generates course corrections. On a UAV, the inner-loop autopilot must respond in a fraction of a second, whereas the outer-loop response time can be much longer.

Two autopilot and navigation options were considered (Table 4). The most capable, and expensive, system listed here is the BAI integrated GPS autopilot, which includes a GPS receiver, altimeter, fluxgate magnetometer, and rate gyro that provide input to a 32-bit computer. This autopilot provides level flight, climb, descent, and coordinated turning under pilot control. The system is also capable of seeking a series of three preprogrammed way points, in which case all control is given to the autopilot computer.

It is also possible to provide outer-loop autopilot control using a 16-bit computer mounted on a PC-104 bus. This bus architecture is rapidly becoming a standard for low-cost stand-alone computer systems. This computer would store GPS way point information and compare it with GPS position information provided by a Trimble GPS board, also available in the PC-104 bus configuration. A compass board that provides serial course data is available, as are low-cost barometric altimeters and wind speed sensors. The computer would monitor this information to calculate course changes required to reach the way point.

Our previous work in developing an onboard computer for an RC model lead us to believe that controls for a UAV system could be developed with greater capability at a lower cost than currently available systems.

Table 4. Navigation and Autopilot Options

System	Weight, kg	Dimensions, mm	Power, VDC × mA = mW	Cost, \$	Capability
BAI 32-bit autonomous flight autopilot	1.4	50×150×200	±7.2×400 = 5760	6500	level flight and turns, constant climb/descent, altitude/heading lock, GPS input, way point seeking, autonomous flight
BTA inner-loop autopilot	0.20	---	4.8×150 = 720	500	level flight and turns, constant climb/descent, altitude lock
Ampro 286 Computer + SSP Serial I/O Board	0.50	50×100×25	2250	1000	16-bit computer with four RS232 ports
Diamond System A/D Board	0.15	50×50×25	1370	600	8-channel 12-bit analog I/O
Trimble GPS Receiver	0.59	100×63×39 +100 dia. × 39 antenna	---	700	3D position within 100 m, differential within 5 m
Wind speed sensor	---	---	---	100	---
Altimeter	---	---	---	100	---
KVA Compass	0.06	46×114×50	500	675	RS232 compass heading
TOTAL	1.4	---	4840	3675	---

We also contacted several experts in the field of aircraft controls, including Dr. Anthony Healy at the Naval Post Graduate School and Dr. Stephen Crow, who is director of the Space Engineering Research Center at the University of Arizona. Both have developed flight control algorithms (inner and outer loop) that are compatible with a 16-bit computer architecture. The algorithm for outer-loop control should be extremely simple and robust.

The inner-loop control for the aircraft would be provided by the BTA autopilot. This is a simple, highly reliable analog feedback system that incorporates a barometric altimeter to sense changes in altitude and a horizontal gyroscope to sense turns. When the RC controls are trimmed, any change in altitude or heading generates proportional servo signals to restore the aircraft to straight and level flight. RC control signals also allow gentle climb descent and turns. This autopilot eliminates the moment-to-moment workload required of a pilot (or computer outer-loop autopilot) to maintain aircraft stability. It should also be possible to use the BTA autopilot to maintain stability of the aircraft during takeoff from a pneumatic launcher, if the launch speed approaches the aircraft cruise speed. An analog inner-loop autopilot also provides a backup mode for flight stability in case the onboard computer should fail and to allow the pilot to control the aircraft with an RC radio.

The 16-bit autopilot system costs are somewhat lower than the BAI system and provide considerable additional flexibility to the user, since the computer could also control instruments and receive RS232 data.

The additional A/D port in this configuration can also be used to monitor additional flight parameters, such as engine speed, engine temperature, air temperature, and humidity. This configuration also allows transmission of GPS phase data to the ground station for differential GPS calculations.

Communication Data Links

A variety of data link options are listed in Table 5. Flight control at short range can be carried out using a conventional 7- or 8-channel RC system. The range of such a system can be boosted to 5 km for remote applications simply by boosting the power output. We plan to include RC controls on the aircraft for all our development work and to provide a backup system for aircraft control.

Table 5. Data Link Options

System	Weight, kg	Dimensions, mm	VDC \times A = W	Cost, \$	Capabilities
BAI "L" band transceiver	1.4	50 \times 150 \times 200	24 \times 1 = 24	9000	2400-baud data at up to 45-km range + video
Proxim RF Modem	0.21	118 \times 68 \times 40	10 \times 1.25 = 12.5	1000	500-mW, 19.2-kbaud two-way communications, 10-km range
RC Receiver, 72 MHz	---	---	---	100	7 channels; 4 servos and 3 switches, 5-km range with booster

BAI and others offer "L" band data links with high range (line of site to 45 km) and integral UHF video transmission; however, these systems are quite expensive and heavy, and they use significant power. The bandwidth is limited to 2400 baud. The "L" band radio also requires FCC licensing, although temporary-use licenses for these radios are generally relatively easy to obtain in remote areas. In addition, the digital communications protocol on this system is nonstandard RS170, proprietary to BAI. We do not plan to use this system for our development work, but "L" band may prove useful for future applications requiring extended range communications.

Full duplex communications with a UAV can also be achieved through a spread spectrum RF modem transmitting at 19.2 kbaud. Such modems are readily available in small sizes at an order of magnitude lower cost than an "L" band system. These radios do not require an FCC license, so their use is greatly simplified. The range of spread spectrum radio is limited to a few kilometers with a unidirectional ground station antenna. This range may be extended to about 10 km through the use of a directional YAGI antenna on the ground station. This antenna must be pointed at the aircraft by the user in order to maintain communications. We have chosen to use this radio for development work.

Video signals will require a separate transmitter. A 2-W amateur UHF transmitter is available at low cost for video and audio transmission, although the range is limited to 3.3 km and requires a directional antenna. A VCR receiver can be used to receive the onboard video signal, and the PC can be equipped with a video board that takes the NTSC video signal and displays it in a scalable window. UHF video transmission also requires an FCC license. Care must be taken that the UHF signal does not interfere with the data link transmissions.

Battery Power

Two battery options are available, as shown in Table 6. NiCad batteries offer a slight advantage in power per unit weight compared to sealed lead acid batteries; both types are rechargeable. The battery weight for 1 hour of service will be 0.036 kg/W.

Table 6. Batteries

Battery Type	VDC	amp-hr	Weight, kg	kg/W-hr
Sealed Lead Acid	24	1.2	1.14	0.040
NiCad	24	1.4	1.2	0.036

Airframe and Engine

We initially considered using the Senior Telemaster RC model airframe. This extremely low cost design was developed in Germany for pulling lines over valleys in the process of rigging power lines. Woods Hole Oceanographic Institute has used one for air sampling and drifter studies. The design features high stability and payload on an airframe with well-known flight characteristics. A Senior Telemaster with minimum payload will fly at 25 kph (7 m/s) and has a takeoff run of a few meters; increasing the load increases the minimum airspeed and takeoff speed. A completed Senior Telemaster airframe (balsa, hardwood, and plastic skin) is available with a 2.4-m (8-ft) wingspan, maximum payload of 4.5 kg, and payload bay dimensions of 150V × 100W × 300L (0.002 m³). The width of the payload bay is too small for a 645 photogrammetry camera. A kit version of the Telemaster with a 3.7-m (12-ft) wingspan and 9-kg payload is also available; however, these kits require significant additional time and cost to complete, the RC model fittings used may not be compatible with cold weather operations, and the durability of the wooden framework design under field operating conditions is questionable.

In this Phase I project, we chose to modify a low-cost (\$5,500), commercially available, half-scale Pioneer trainer as a feasibility demonstration platform. This aircraft is manufactured by BAI Aerosystems with a fiberglass monocoque fuselage and proprietary composite wing. The 3-hp gasoline engine is mounted aft in a pusher configuration, which provides an unobstructed open area for instruments and avionics ahead of the wing. The existing trainer design has a payload capacity of up to 7.1 kg with 1.8 kg of fuel on board and a large (0.021 m³) payload volume with two access hatches. The volume and payload capacity of this UAV are compatible with the autopilot, computer, and data link with room for most of the scientific instruments listed in Table 2.

Stall speed at maximum load for the Pioneer trainer is 70 kph (40 kts) with a maximum speed of 130 kph (80 kts) and cruise speed halfway in between. The Pioneer trainer stall speed is too fast for loitering in a breeze, and the wing design of the Clark Y used on the Pioneer is known to be relatively inefficient. We therefore modified the aircraft design to incorporate a high-lift, low-Reynolds-number wing. The wing area is double that of the trainer with a wingspan of 3.66 m (12 ft) and a chord of 0.406 m (16 in.). The airfoil used is the RF-1165FB developed by the Naval Research Laboratory as part of their work on low-speed electronic warfare decoys. This wing has a lift coefficient of 1.2, which is significantly greater than the Clark Y design used on the trainer ($C_L = 0.8$). QUEST fabricated the spars and ribs for this wing from NOMEX honeycomb composite (Figure 1); spars and ribs used by BAI are normally constructed from plywood, but NOMEX was used to build a wing of the same weight but twice the area and 3 times the lift. The net maximum payload capacity was expected to increase dramatically.

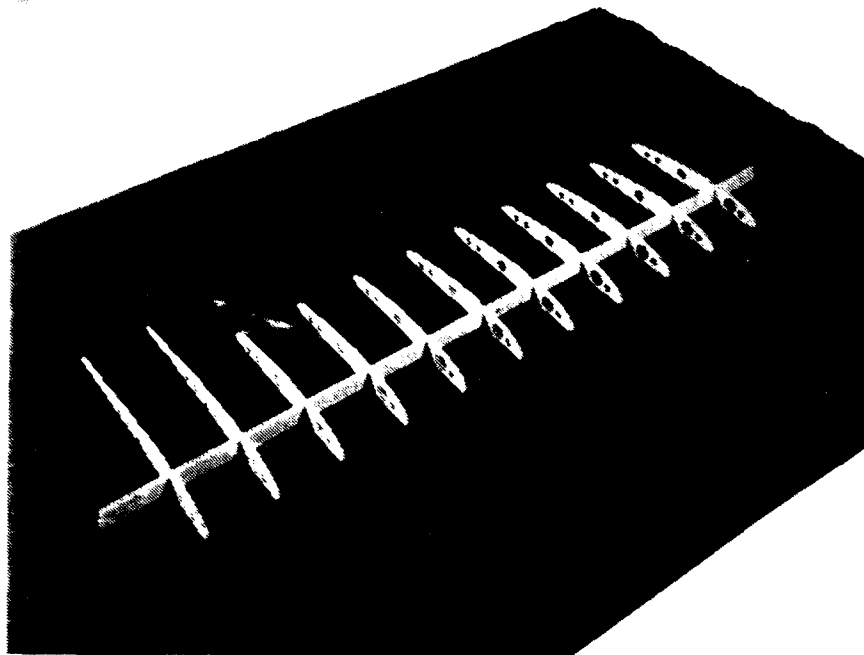


Figure 1. NOMEX Rib and Spar Construction for RF-1165FB Wing

The lift capacity of a wing (in kilograms) is related to its speed and area by

$$m = \rho A C_L V^2 / 2g$$

where ρ is the density of air (1.22 kg/m^3), A is the wing area (1.5 m^2), C_L is the lift coefficient, V is the airspeed (m/s), and g is the acceleration of gravity (9.8 m/s^2). The stall speed is the speed at which the lift capacity equals the aircraft mass; this is also the takeoff speed. Stall speed is thus a function of gross aircraft weight. The maximum aircraft speed is limited by its propeller power, P_p , and drag coefficient, C_{do} :

$$V_{max} = (P_p / \rho A C_{do})^{1/3}$$

The UAV design specifications and calculated capabilities are listed in Table 7.

Abrasive-waterjet cutting was used to ensure a dimensional accuracy of 0.1 mm on the wing ribs. This accuracy is required to attain proper aerodynamic performance of a low-Reynolds-number airfoil. The wing was completed by BAI using their proprietary foam core composite skin technique. Unfortunately, this technique did not faithfully reproduce the airfoil shape, as shown in Figure 2. Airfoil shape errors in excess of 5 mm were generated during placement of the foam composite. The most severe errors occurred in the leading-edge portion of the wing, which is most critical to airfoil performance. We therefore expect the lift coefficient of the foam core composite wing to be comparable to a conventional flat-bottom wing design such as the Clark Y. Nonetheless, we expect that this wing should be capable of flying at a gross vehicle weight of up to 45 kg and should easily fly at a weight of 30 kg (66 lb). We have also concluded that the foam core composite skin technique used by BAI is not appropriate for the fabrication of precision, high-efficiency, high-lift airfoils.

Table 7. Low-Cost UAV Design Specifications

Speed	50-75 kph (25-40 kts) stall	140 kph (75 kts) maximum
Aircraft Weight	20.5 kg (45 lb) empty	45 kg (100 lb) max gross
	30.5 kg (65 lb) normal load	
Endurance	10 hrs w/ 10 kg payload	2 hrs w/20 kg payload
Range	10 km w/telemetry	200-1000 km autonomous
Wing	3.66 m (12 ft) span	RF-1165FB airfoil
	0.41 m (16 in.) chord	$C_L = 1.2$ (1.3 with flaps) $C_{do} = 0.35$
Length	1860 mm overall	1257-mm fuselage
Engine	Quadra42 gas/oil mixture	propeller power
	$P_e = 2.2$ kW (3 hp) fuel consumption = 1.3 kg/hr	$P_p = 1.8$ kW (2.4 hp)

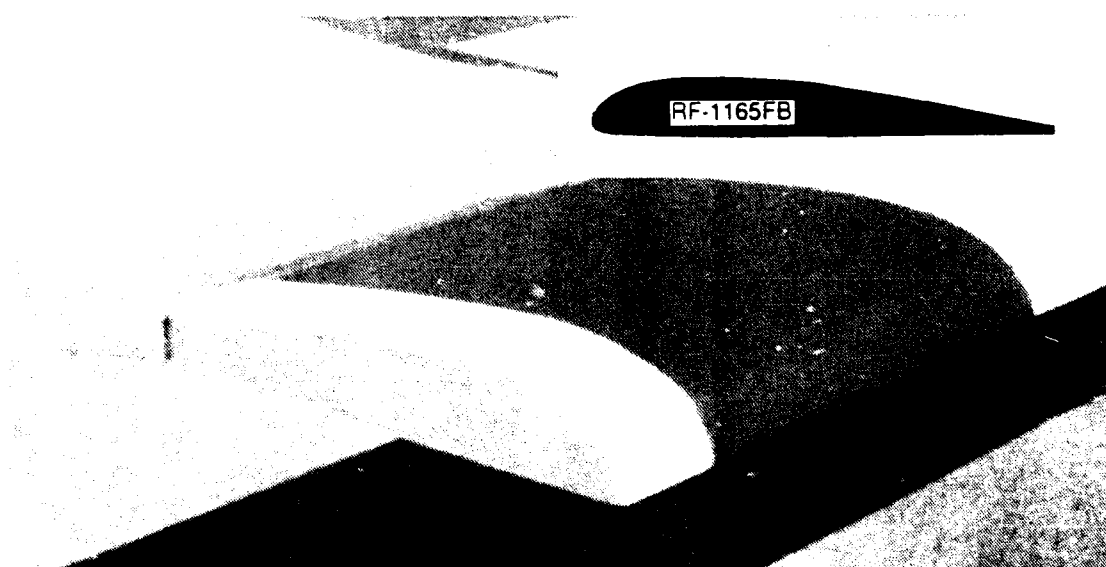


Figure 2. Wing Detail Showing Flat Spots and Large Deviation from Design Airfoil (RF-1165FB shown in inset)

A four-stroke, gasoline engine is used to power the UAV. These engines provide greater efficiency than two-stroke, glow-plug engines used on most RC models. For high-altitude flight, a temperature sensor will be mounted on the engine exhaust to provide a control signal for a servo fuel mixture control.

Parachute

The parachute will be mounted in an over-the-wing compartment with a spring-loaded door and servo release. The servo can be activated manually or armed for automatic deployment if the aircraft drops below 500 ft, if the engine stops, or if control is lost for some other reason. Parachute deployment will involve stopping the engine; the propeller can be mounted to come to rest in a horizontal position so that it does not interfere with parachute deployment. The aircraft will then be maneuvered into a slow-speed, nose-high attitude, and the parachute compartment cover will be released; drag on the cover will pull the parachute out.

We ordered a parachute made for the UAV from Navillus Industries in Texas; however, they were unable to deliver the parachute three months after placement of the order.

A parafoil recovery system is available for the BAI Exdrone that weighs about the same as the oceanographic UAV.

Catapult

A catapult could be used to simplify launch and to allow launch from a confined space, such as a ship or coastline. Assuming a takeoff speed of 50 kph (25 kts), the catapult must be capable of accelerating the 40-kg UAV (20-kg payload) at an acceleration of 40 m/s^2 (4 g) over a distance of 2.5 m (8 ft); the force required is 1600 N (360 lbf), which could be supplied by a compressed air cylinder.

The pneumatic catapult used for the Exdrone is 8-m (26-ft) long, including guide rails, and requires its own trailer. This system is manufactured by Continental RPV and is capable of launching a 50-kg aircraft at a speed of 80 kph (45 kts). A portable system (160 kg) capable of launching the oceanographic UAV is also available from Continental RPV.

FLIGHT TESTING

Aircraft Configuration

The modified trainer aircraft delivered by BAI is shown in Figure 3. The wing is designed to be easily removed and breaks down into three 1.2-m (4-ft) sections. The tail can also be removed and broken down for easy transport. Examination of the aircraft revealed that the aluminum spar tubes that support the outboard wing segments were undersized and in fact these tubes buckled when the aircraft was lifted by its wing tips. A buckling calculation was made, and more substantial replacement spar tubes were fabricated.

Test Pilot

Our flight tests were carried out by Mr. Les Kimsey, an experienced RC-model pilot. Mr. Kimsey has over 20 years of experience flying RC aircraft, including aircraft larger than the Pioneer trainer. He has been head flight instructor for the Boeing Hawks RC flying club for the past 10 years, and he carried out all of the test flights on QUEST's previous UAV project.

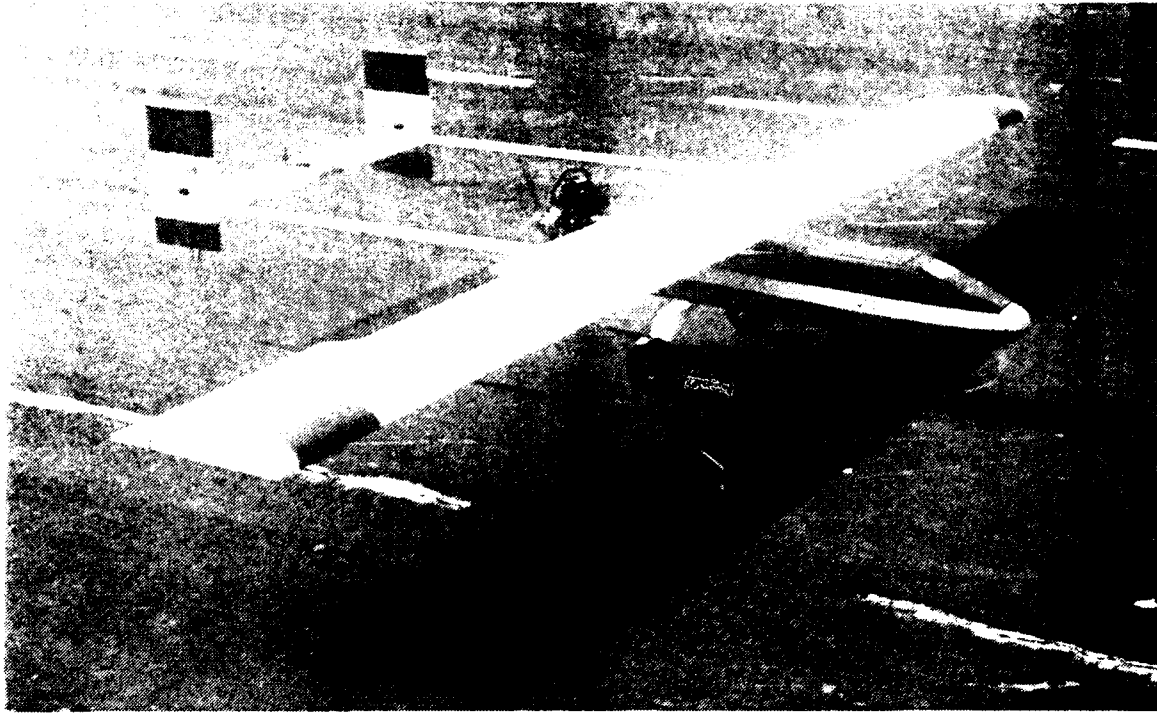


Figure 3. Pioneer Trainer Aircraft with "High Lift" Wing

Aircraft Modifications

Initial high-speed taxi tests showed that the aircraft had no tendency to rotate into a takeoff attitude; in other words, the aircraft delivered to us was incapable of flight. We therefore carried out a detailed analysis of the aircraft configuration and concluded that the center of gravity was located too far forward of the main landing gear to allow takeoff. In addition, the landing gear was too short to allow rotation to a reasonable takeoff angle before the propeller would hit the ground. We therefore carried out a number of design modifications. An aeronautical engineer familiar with the design of ultralight aircraft was enlisted to assist in this effort and to verify our design calculations.

We first moved the main wing as far back as possible on the fuselage. This provided a center of lift and center of gravity closer to the main gear mounting points. We also extended the main gear to provide sufficient prop clearance. Finally, we balanced the aircraft to a center of gravity of 33% of the wing chord as opposed to the 25% used by BAI. This still provides a large stability margin and is a much more typical configuration for an aircraft. Our consultant cautioned that the elevator surface area provided was marginal for this aircraft but that it should still fly reasonably well. We refer to this modified aircraft as the Mk1.

Mk1 Flight Tests

Our first takeoff required the entire available runway for takeoff. The aircraft handled reasonably well but lacked elevator authority, as expected. The first landing was fairly hard because it was necessary to land at a relatively high speed to maintain elevator control. The aircraft was checked and was operating normally. We attempted a second flight to further test handling and stability, but the receiver radio on the aircraft failed, and the plane crashed. We believe that the first hard landing damaged the radio, causing an intermittent failure and the crash.

Damage to the aircraft was limited primarily to the fuselage and tail, with little or no damage to the wings and engine. We therefore rebuilt the aircraft using a new fuselage. The tail was rebuilt in a high "T" configuration to move the stabilizer above the turbulence behind the fuselage and engine. We also doubled the elevator stabilizer area. We calculated servo torque loads and found that all the major control surface servos were inadequate. These were all replaced with appropriate servos. In addition, the single elevator servo was replaced with dual servos in a redundant configuration. The aluminum landing gear was replaced with a music wire gear to reduce weight, provide the appropriate gear height, and provide shock resistance for landings. This Mk2 high tail aircraft is shown in Figure 4.

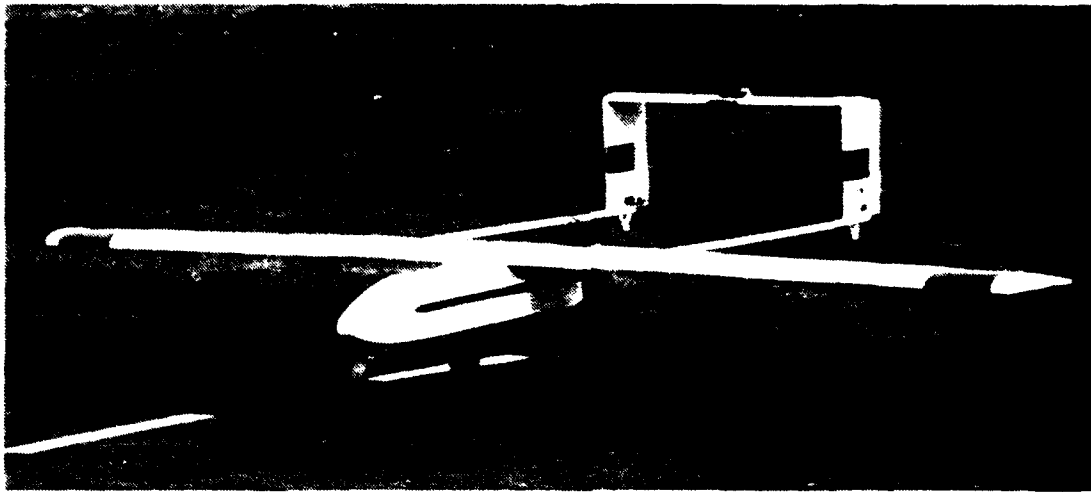


Figure 4. Mk2 High Tail Configuration

Mk2 Flight Tests

Four test flights of the Mk2 aircraft were carried out. The aircraft carried a dummy payload of 4 kg (9 lb) plus 1 kg of fuel on all tests. The first flight tests showed a substantial improvement in aircraft handling, particularly elevator authority. This allowed a much shorter takeoff roll and controlled, low-speed landings. On the second flight we observed the maximum speed to be 110 kph (60 kts) and the stall speed with full flaps was less than 18 kph (10 kts).

The Mk2 aircraft was also flown to test the BTA inner-loop autopilot. The autopilot was installed between the radio and servos. The aircraft was flown initially without autopilot to set the aircraft trim to straight and level flight. The autopilot was adjusted on the ground until the turning of the autopilot on or off had no effect on the control surfaces when set in their trim positions. On the second test flight, the aircraft was flown straight and level at a cruise speed of 90 kph (50 kts) and the autopilot was turned on. When no control signal was provided, the aircraft flew straight and level. A right stick caused the aircraft to initiate a gentle, level right turn. The autopilot was turned off in the course of this turn and the pilot initiated a hard turn. This action apparently caused a wingtip stall, and the aircraft went into a spin and crashed. This incident illustrates the difficulty that a UAV pilot can have when dealing with an unusual aircraft maneuver at a relatively long distance (almost 300 m).

CONCLUSIONS

This Phase I study has demonstrated the feasibility of an oceanographic research UAV by specifying performance requirements, identifying low-cost control, communications, navigation, data acquisition, and instrumentation systems and demonstrating that a low-cost airframe can carry these systems.

Table 8 lists the components of a complete UAV system including weights, dimensions, power requirements, and cost. The aircraft listed was fabricated with a fiberglass fuselage and composite wing built with NOMEX ribs and spars and a fiberglass/foam core composite skin. This fabrication process did not result in an acceptable airfoil, but the wings were extremely durable.

Table 8. Feasibility Demonstration System

System	Weight, kg	Dimensions, mm	Power, W	Cost, \$
Modified Pioneer Trainer, 3-hp engine and high-lift wing	9.8 Payload +12.7 Empty	175V × 150W × 775L (= 175+375+225)	—	7,200
16-bit computer autopilot, w/GPS & compass	1.4	100×100×100	4.8	3,675
Proxim RF Modem	0.2	118×68×40	12.5	1,000
Batteries (2 hr @ 0.036 kg/W-hr)	1.2	25×100×150	—	20
Parachute	0.5	150×150×150	—	180
Fuel (2 hr @ 1.3 kg/hr)	2.6	125×125×125	—	—
Maximum payload	3.9	—	—	—
TOTAL	9.8		17.3	12,075

The Mk2 aircraft handled extremely well with a 5-kg payload and gross weight of 20 kg and is easily capable of taking off and cruising at the higher speeds required to carry a 10-kg payload. This aircraft thus has the capability of carrying a 3.9-kg payload for a minimum of 2 hours. A number of simple modifications to the aircraft design will further increase payload capacity. These include eliminating the landing gear for drag reduction, providing an aerodynamic cowling around the engine, and using a more efficient wing design. The wing produced for this aircraft did not meet our design specifications; a proper airfoil should improve lift and efficiency by 50%.

The total purchased aircraft component cost was slightly over our target of \$10k; however, the individual component costs are reasonable.

Our preliminary flight tests demonstrated stable flight with a low-cost inner-loop autopilot. We also learned that even the most experienced pilot is capable of losing an aircraft. The most critical development required for the success of UAVs in research is to eliminate the pilot from the control loop.

Discussions of UAV applications with a number of researchers indicate that there is a real need for this capability. A reliable low-cost system capable of carrying modest payloads would enhance the cost-effectiveness of programs that presently rely upon helicopter support. More importantly, such a system would allow more frequent and longer-term monitoring of the temporal variability of a wide range of

oceanographic processes, such as upwelling events, sea ice deformation, coastal current evolution, tidal processes, and plankton growth. The availability of aircraft support in remote regions would also provide greater ability to carry out synoptic research programs that integrate satellite data, underwater measurements, and atmospheric data.

Progress in oceanography depends critically on our ability to sample the environment, and the development of an oceanographic UAV will greatly enhance that capability.

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